Payload Interoperability Testing for the Mars '01 Landed Mission[1]

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Abstract— The Jet Propulsion Laboratory's Mars Surveyor Operations Project (MSOP) is sending it's next pair of spacecraft, an orbiter and a lander, to Mars in 2001. Success of the Mars '01 lander's primary mission objectives relies heavily on the interaction of the various payloads. The Payload Interoperability Testbed (PIT) is being developed at JPL to serve as a key verification facility for the Mars '01 project. The PIT provides a facility for testing payload interoperability functionality and sequences as well as an environment to train personnel for landed surface operations. This paper will define and describe the rationale for the PIT, its architecture, and the current test plan that has been developed for the PIT activities in support of the Mars '01 landed mission.

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1. INTRODUCTION

Following on the heels of the Mars'98 lander and orbiter, scheduled to reach Mars at the end of 1999, the Mars '01 spacecraft pair will continue the campaign for understanding the red planet's resources, climate, and evidence of life, past or present. Landing on Mars in January of 2002, the Mars '01 payloads will perform their 21-day primary mission with the capability for a full mission to be completed in 90 days.

Lockheed Martin Astronautics (LMA) in Denver, CO, is the system contractor for the Mars '01 lander and orbiter. The Mars' 01 lander will carry Marie Curie, the spare Sojourner rover of Mars Pathfinder fame. Like Viking and Mars '98, the Mars '01 lander will have a robotic arm, but this arm will have an additional responsibility beyond scooping Martian soil samples for scientific analysis. The Mars '01 Robotic Arm (RA) will deploy the Marie Curie rover by grappling, lifting, and placing it safely on the surface of the planet. The rover deployment by the robotic arm adds a new technical challenge to the design, test and operation of the Mars '01 mission.

The lander payloads have a high degree of interaction for most of the critical mission activities (i.e., rover deployment, soil sample delivery, rover navigation). The PIT is being developed at JPL to mitigate the risk and schedule impact of performing these activities on the flight lander in Assembly, Test & Launch Operations (ATLO) and as a training ground for mission operations. The PIT will have a set of lander interoperable payload hardware integrated on a flight-like lander deck. Initial testing in the PIT will focus on verifying primary mission objectives such as rover deployment and robotic arm soil sample delivery. Later in the test flow, Sequence Verification Tests (SVTs) will be developed and tested in the PIT in support of the flight lander ATLO activities at LMA. The PIT will also be used for troubleshooting any payload problems encountered during ATLO that cannot be debugged on the flight spacecraft. Near the end of the ATLO phase, the PIT will be moved from a Class 100K clean room to a sandbox facility. This sandbox will be used for operational readiness testing during which the operations team will validate the landed mission sequences, processes, and procedures.

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2. THE PIT DEFINED

What is the PIT?

The PIT contains a subset of payload hardware on a mock-up of the lander deck, a lander simulator running integrated lander and payload flight software, a power simulator, and workstations running the Ground Data System (GDS). Figure 1 provides a look at what will be developed in the PIT. Further description of the PIT payload hardware is given in Section 3.

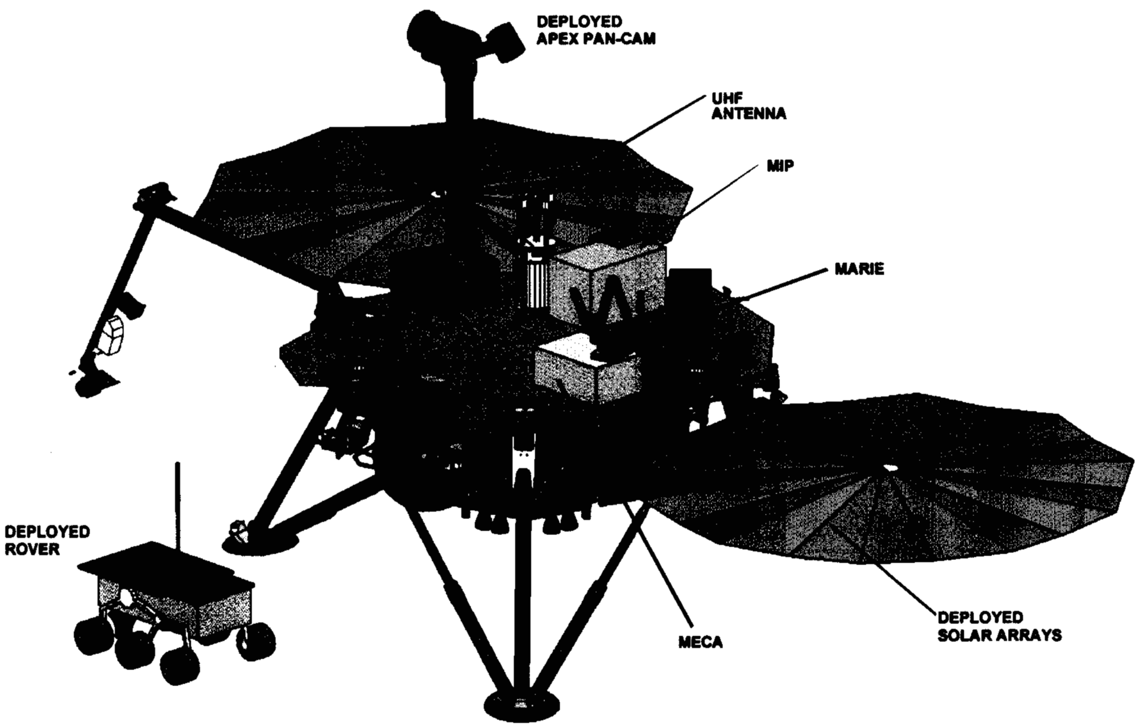

Figure 1. Mars '01 Landed Configuration

The Purpose of the PIT

The primary purpose of the PIT is to mitigate risk to the landed mission by testing those payloads that have a high degree of interaction with each other in executing the most critical mission activities. The PIT will be used to test critical system-level integrated payloads for the landed operations Baseline Reference Mission (BRM) plan development and validation. The PIT will support the ATLO activities at LMA by preparing and SVT sequences as well as troubleshooting landed payload problems during ATLO. A subset of tests will be performed in the PIT that cannot be performed on the flight lander in ATLO such as delivering actual soil (or "clean dirt") and digging with the robotic arm. Off-nominal and contingency plans will also be validated in the PIT.

The PIT will verify critical interoperability activities for development and validation of the landed mission plan. For example, these activities include: unstowing of the Robotic Arm (RA), rover dust cover removal, rover stand-up, rover Alpha Proton X-Ray Spectrometer (APXS) calibration, rover grappling, rover deployment, rover navigation, RA soil delivery to the Mars Environmental Compatibility Assessment (MECA) experiment, MECA drawer images, MECA microscopy and wet chemistry, Panoramic Camera (PanCam) and RA Camera (RAC) engineering support imaging, RA Mössbauer (MB) calibration, and RA patch plate deployment. These activities are tested in the PIT via a series of landed scenario sequences.

As an example of the interoperability of the payloads, the deployment of the rover by the robotic arm sequence relies on images from the RAC to verify each step of the process including grappling, lifting, moving out beyond the lander deck, lowering to the surface, and degrappling. Following each step in which a RAC image is taken, the image data must be transmitted to earth and engineers on the ground must assess from the image whether the action was successfully completed before commanding the payloads to proceed. Given the daily downlink passes via the Mars '01 orbiter to relay data from the lander to the earth, the rover deployment sequence could take up to seven days to complete. A detailed list of the rover deployment requirements is provided in Section 4 under "PIT Requirements Verification."

The prelaunch testing performed in the PIT will serve as valuable training for landed operations. In this environment, test engineers will gain valuable insight into the payload characteristics and idiosyncrasies that will enable them to support the dynamic 21-sol primary mission. Operations procedures, sequences, teams and interfaces will be formally validated during the operational readiness tests several months before the lander is launched.

3. PIT ARCHITECTURE

The Lander Payloads

The interoperable payload set includes the Marie Curie Rover, RA, RAC, MECA including an electrometer mounted on the base of the RA scoop, and the Athena Precursor Experiment (APEX – Athena is the Mars Sample Return '03/'05 rover) package consisting of the APXS mounted on the rover, the PanCam mounted on a deployable mast, the MBspectrometer mounted on the RA, and a Miniature Thermal Emission Spectrometer (Mini-TES). Figure 2 shows the payload hardware and illustrates the various component interfaces.

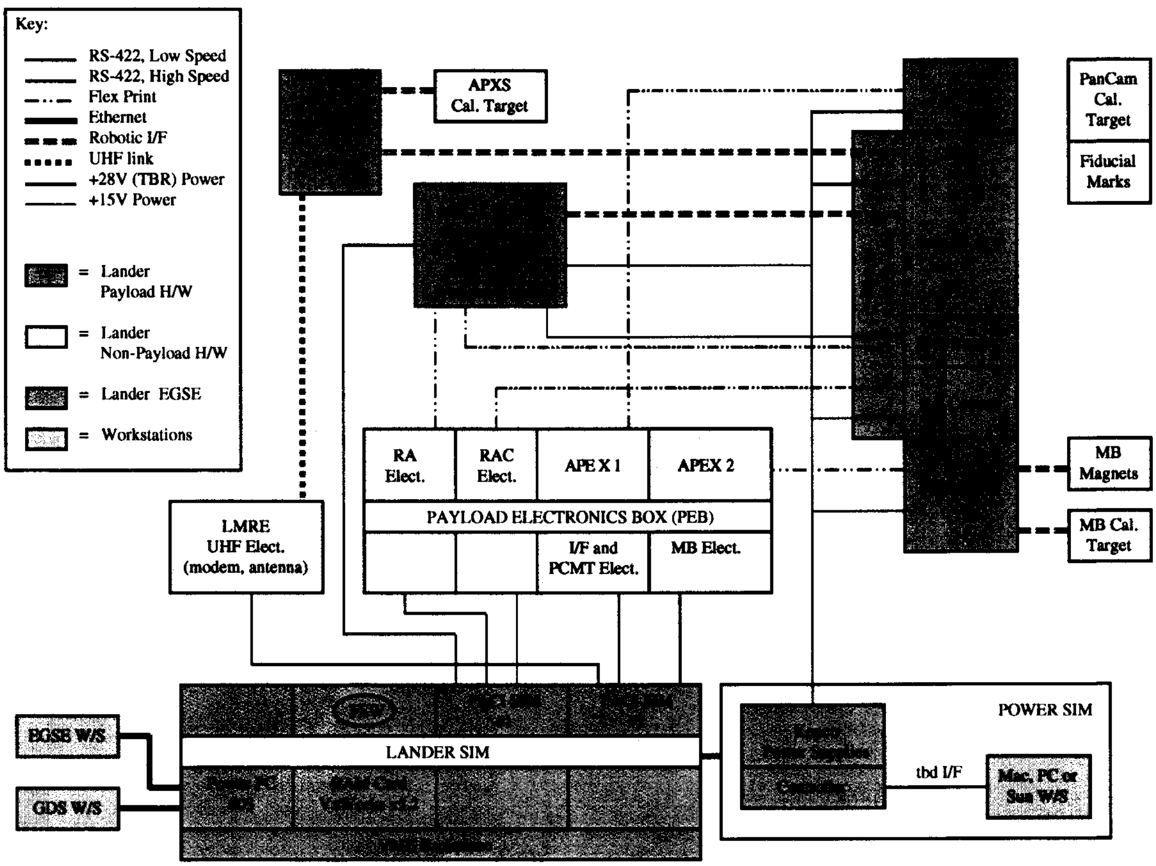

Figure 2. PIT Block Diagram

MECA, through its various experiments, will try to determine if Martian dust and soil pose a hazard to the human exploration of Mars. In addition to these payloads, the Mars '01 Lander contains a Mars In-situ Propellant Production Prototype (MIP) and a Mars Radiation Experiment (MARIE). MIP and MARIE, however, primarily operate independently of the others; therefore, they will not be integrated into the PIT.

The Lander Simulation

The Lander Simulation (Lander Sim) provides the electrical interface to the payloads in the absence of an actual Lander Avionics system. The flight lander avionics consists of a RAD6000 processor hosting the lander flight software (FSW), and the flight Payload & Attitude Control Interface (PACI) cards. To reduce cost for the test environments, the Lander Sim was developed. It contains a Power PC processor hosting a portion of the lander FSW, and PACI simulator (sim) cards which are commercial-grade equivalents of the flight PACI cards. The Power PC, a memory card and 2 PACI sim cards are integrated into a VME chassis in the PIT configuration. High-speed and low-speed RS-422 interfaces from the PACI sim cards are cabled to the Payload Electronics Box (PEB) interface cards to provide command and data communications from the FSW to the payloads.

The Payload Electronics Box

The Payload Electronics Box (PEB) is a chassis and set of cards that provides electrical interface between the PACI sim cards in the Lander Sim chassis and the individual payloads. Included in the PEB are the RA electronics, RAC electronics, and APEX (PanCam & MB) electronics. The cabling from the PEB to the payloads is flex print routed on the surface of the lander deck.

Additional Payload-Related Hardware

In addition to the payloads, there is a set of hardware that is used to support payload functionality and operation. There is Lander-Mounted Rover Equipment (LMRE) including the rover modem and antenna. The LMRE is mounted on the lander deck with an RS-422 interface to a PACI sim card. There are several calibration targets mounted on the lander deck for the APXS, PanCam, RAC and MB Spectrometer.

The Ground Data System (GDS)

The GDS provides hardware and software for telemetry processing and sequence generation along with supporting network infrastructure. It interfaces with the Lander Sim to provide basic telemetry processing and visualization, and provides processing of telemetry into packets and channelization of data that can be queried by users. A primary goal of the GDS effort is to develop a consistent set of multimission tools for the PIT, ATLO and mission operations.

4. THE PIT TEST PLAN

Receivables / Deliverables (REC/DELs)

Payload hardware, ground support equipment, FSW, GDS, and sequences are delivered to the PIT for integrated testing. Once the sequences are tested and validated in the PIT, they are delivered to LMA's Spacecraft Test Laboratory (STL) where they are executed before being run on the flight lander in ATLO. Figures 3-6 are the integrated test flow diagrams which illustrate the REC/DELs and detail the schedule for the PIT activities.

Integrated Test (IT) Flows and Definitions

Hardware delivery blocks are shown at the top of the test flow diagram and essentially drive the definition of the integrated tests. FSW and GDS deliveries are made approximately two weeks ahead of their related hardware deliveries. The FSW, GDS, and sequence deliveries are indicated below the integrated test blocks. Delivery dates are shown in the upper left on each box, and the number of days for each activity is shown to the upper right.

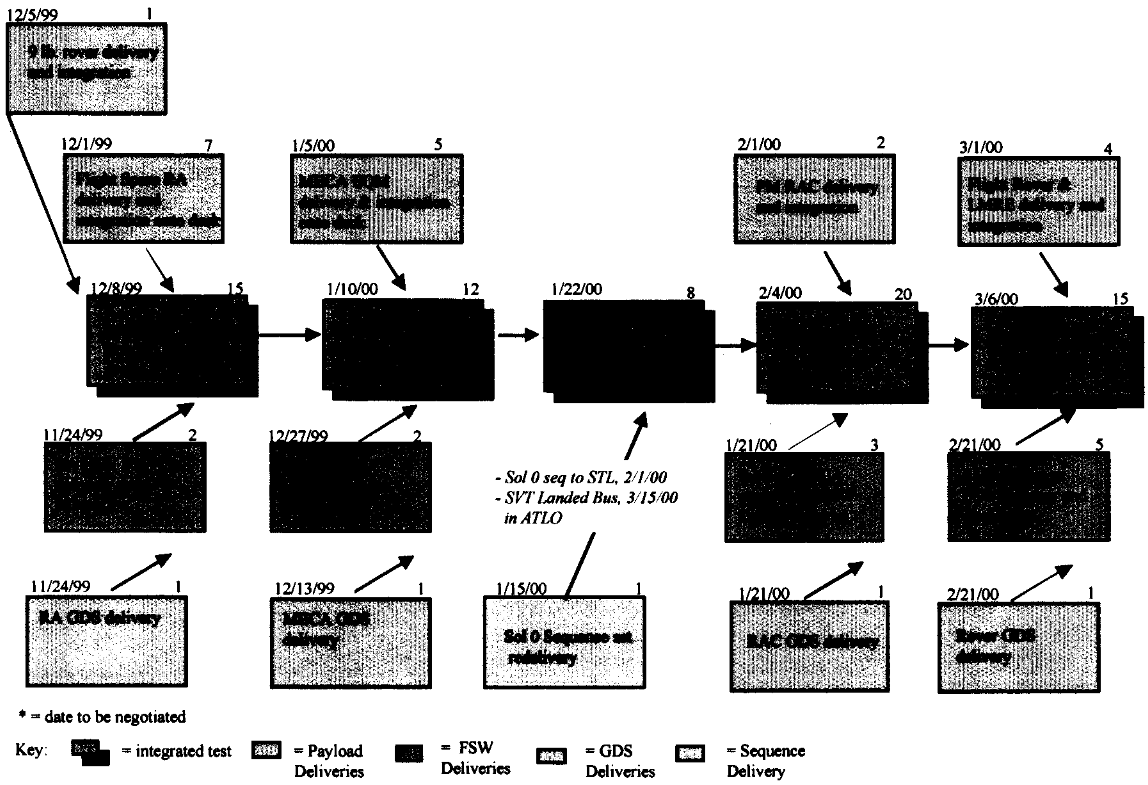

Figure 3. Integrated Test Flow (1 of 4)

IT #1: RA / 9 lb. Rover Deployment— In this first integrated test, the RA will be unstowed and commanded to various specified positions. This motion will be verified both visually and with telemetry provided by the GDS. Limited range of motion, keep-out zones and clearance tests will be performed with the RA to understand the volumetric constraints of the lander deck, lander legs and other payloads on the deck to the required motion of the RA. RA control to grapple and deploy the 9 lb. rover to the surface will be demonstrated under nominal conditions and various tilt angles of the lander deck. The 9 lb. rover is a simple mass model that is safe for the RA to lift in Earth gravity and that approximates the gravity ratio that the arm will experience on Mars.

IT #2: RA / MECA— In IT #2 the MECA wet chemistry cell drawers will be commanded to open and the choreography of simulated soil delivery with the RA will be performed. Since the RAC is not yet integrated, verification of RA position at the MECA drawer will be made visually. The MECA drawers will then be commanded to close. The electrometer, mounted on the bottom of the RA scoop, will be tested by powering it on, controlling the RA position of the electrometer to various locations, and verifying its sensor data through the GDS.

IT #3: Sol 0 Sequence— IT #3 will verify the actual first Sol 0 (Sol = Martian day) sequence in support of a February '00 delivery to the STL and a March '00 landed bus SVT in ATLO. The Sol 0 sequence includes payload health checks, APEX mast deployment, unstowing of the RA, a PanCam panorama, and night operations activities.

IT #4: RA / RAC / MECA— It #4 is the first integrated test with the RAC. In IT #4 RAC images will be used to verify the RA soil sample (i.e., "clean dirt") delivery to the MECA wet chemistry cell drawers. Also in IT #4, the MECA microscopy experiment and adhesion patch plate operations with RAC imaging will be performed. MECA microscopy consists of unsafing the MECA sample wheel/translation stage (SW/TS), rotating and translating the SW/TS, delivering soil samples to the SW/TS with the RA, RAC image verification of the soil delivery, abrading and scraping the samples in the SW/TS, imaging the sample with the MECA optical microscope and Atomic Force Microscope (AFM), processing the images with the

RAC electronics, and resafing the SW/TS. The Adhesion Patch Plate operations consist of releasing the adhesion patch plate with the RA and verifying it with RAC imaging, RA simulation or delivery of soil to the patch plate, removal of soil from the patch plate by "twanging" it with the RA, and verifying it with RAC imaging.

IT #5: RA / Flight Rover— IT #5 is the first integrated test performed with the actual flight rover and the rover FSW. In IT #5 the flight rover will be commanded to stand-up and roll back and forth, thereby releasing itself from the lander deck. The flight rover will then be operated to place the APXS on the calibration target. In another test of rover deployment, the RA is controlled to the grapple to the surface and another RAC image will be taken of the rover at the deployment site. The RA then disengages the rover and a RAC image of the disengaged rover is taken. IT #5 will include a RAC workspace panoramic image.

IT #6: Rover / PanCam— IT #6 focuses on the PanCam interoperability with the flight rover. It will include a PanCam spectral spot cube of the sample site, PanCam pointing characterization and pointing repeatability images for the rover team, PanCam and RAC images of the stowed and standing rover, a PanCam predeploy terrain panorama, rover deployment with PanCam image verification of grappling (9 lb. Rover swapped in for

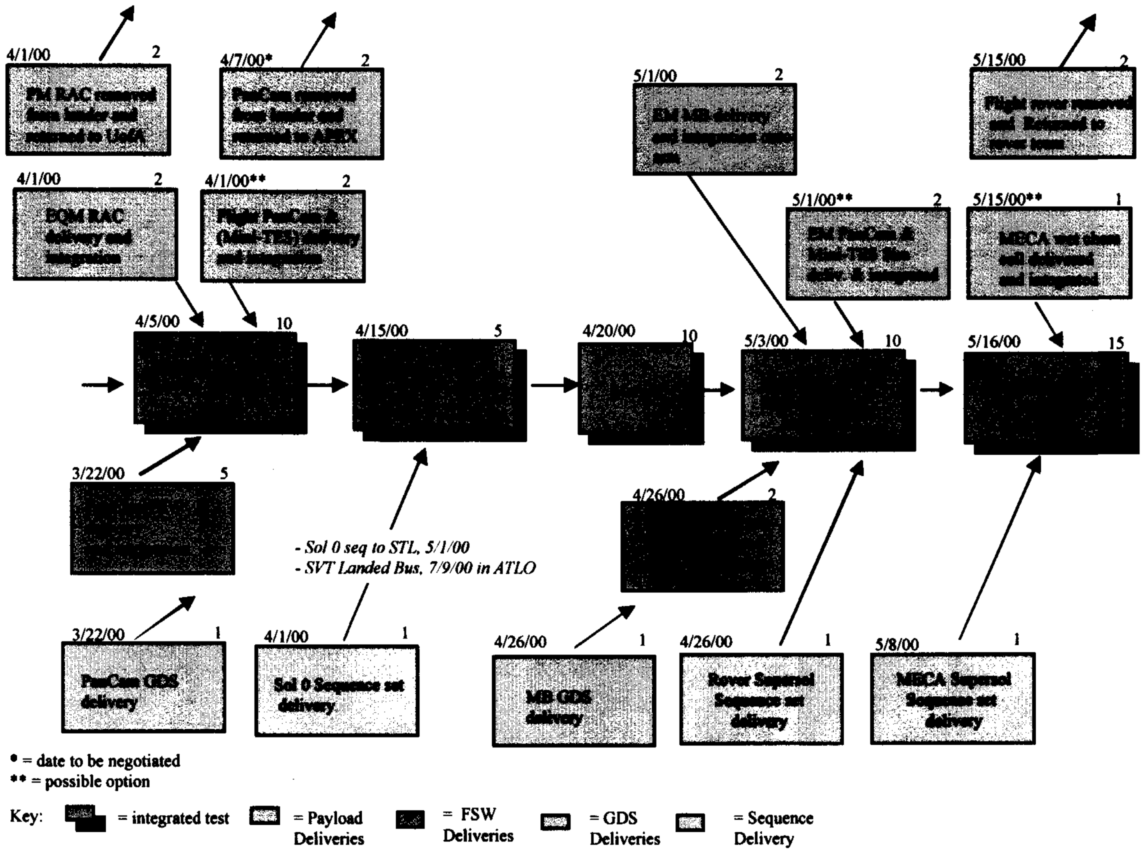

Figure 4. Integrated Test Flow (2 of 4)

position on the flight rover and RAC image verification is performed. The flight rover is then removed from the lander deck and the 9 lb. rover is swapped in for the deployment activity (to protect the robotic arm in earth gravity). The RA will grapple and deploy the 9 lb. rover actual deployment), and a PanCam image of the rover at the deployment site and disengaged from the RA. These interoperability activities are primarily in support of rover navigation which is verified by sequence in IT #8.

IT #7: Sol 0 Sequence Update— IT #7 is a sequence update of IT #3 in which the following payloads will have been integrated in addition to the robotic arm: RAC, MECA, flight rover, flight PanCam (possibly).

IT #8: Rover Supersol Sequences— IT #8 is a rover-focused sequence verification test that will be performed with the PanCam. Each of these sequence activities will have been functionally verified in previous Integrated Tests. The Rover Supersol sequences are under development and presently include rover dust cover removal, standup, APXS calibration, grapple, deploy, ungrapple, and navigation.

IT #9: MECA Supersol Sequences— IT #9 will also be performed with the PanCam and focuses on MECA activities. Again, each of these sequence activities will have been functionally verified in previous integrated tests. IT #9 includes opening of the patch plate with the RA, MECA wet chemistry, optical microscope imaging, and closing of the patch plate with the RA.

IT #10: Sol 0 Sequence Update, Sol X Sequence— IT #10 is a Sol 0 sequence update of IT #7 and the first test of what is known as the Sol X sequence. The Sol X sequence is a collection of activities not included in either Sol 0, the Rover Supersol or the MECA Supersol, but that are important to the landed mission. Sol X includes imaging of the PanCam fiducial marks, calibration target and spectral spot, PanCam panorama images, the RAC workspace panorama, electrometer activities, MB calibration and Mini-TES activities.

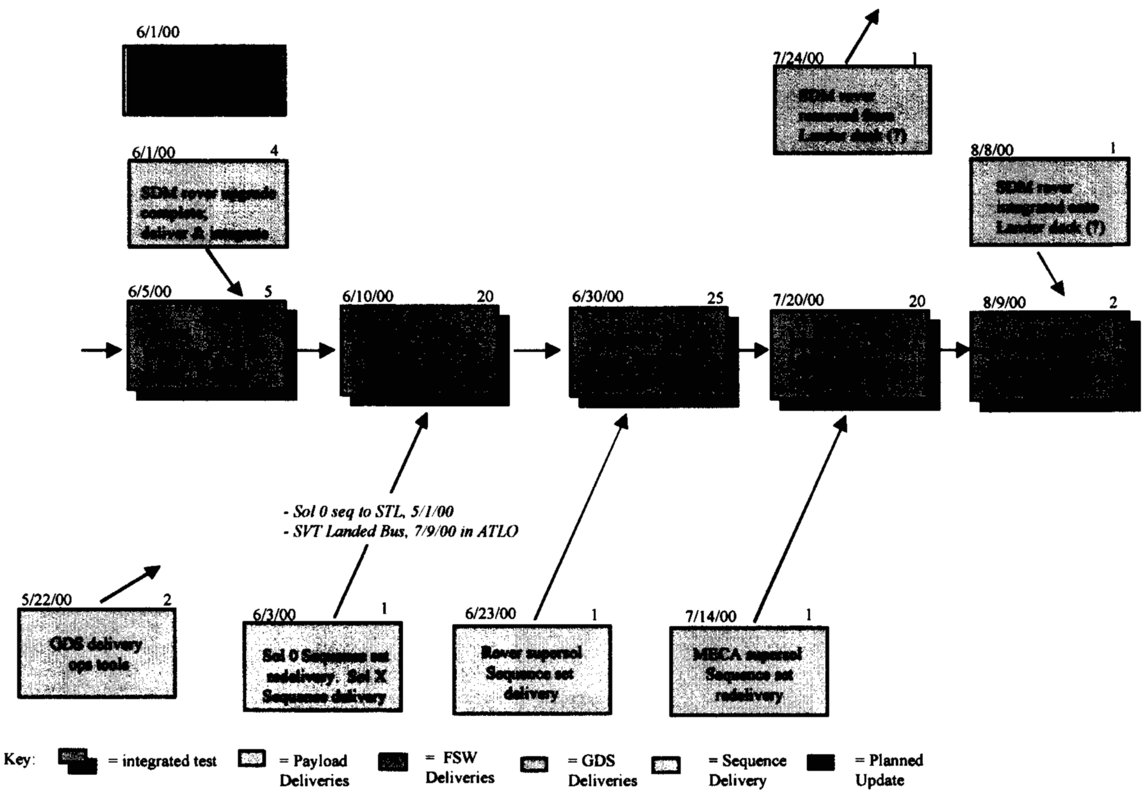

Figure 5. Integrated Test Flow (3 of 4)

IT #11: Rover Supersol Sequences— IT #11 is a sequence update of IT #8. Any changes required as a result of sequence planning, development, or testing in the STL at LMA will be incorporated and retested in the PIT.

IT #12: MECA Supersol Sequences— IT #12 is a sequence update of IT #9. Any required changes to the sequences are retested in the PIT.

Baseline Payload IT (BPIT)— The BPIT is an interface verification between all payloads, the PEB, and the Lander Sim. This test was identified due to the scheduled move (August '00) of the PIT to a new building currently under construction at JPL. It is executed prior to moving the PIT to baseline the interface functionality. It is executed again following the move and reintegration of the PIT facility to ensure the system is properly

Payload Requirements Verification

The ITs described above were developed based on the level 4 payload requirements derived at the system level. A verification matrix is maintained which traces the test, by procedure number, that will satisfy each requirement. The table below details rover deployment-related requirements as extracted from the verification matrix.

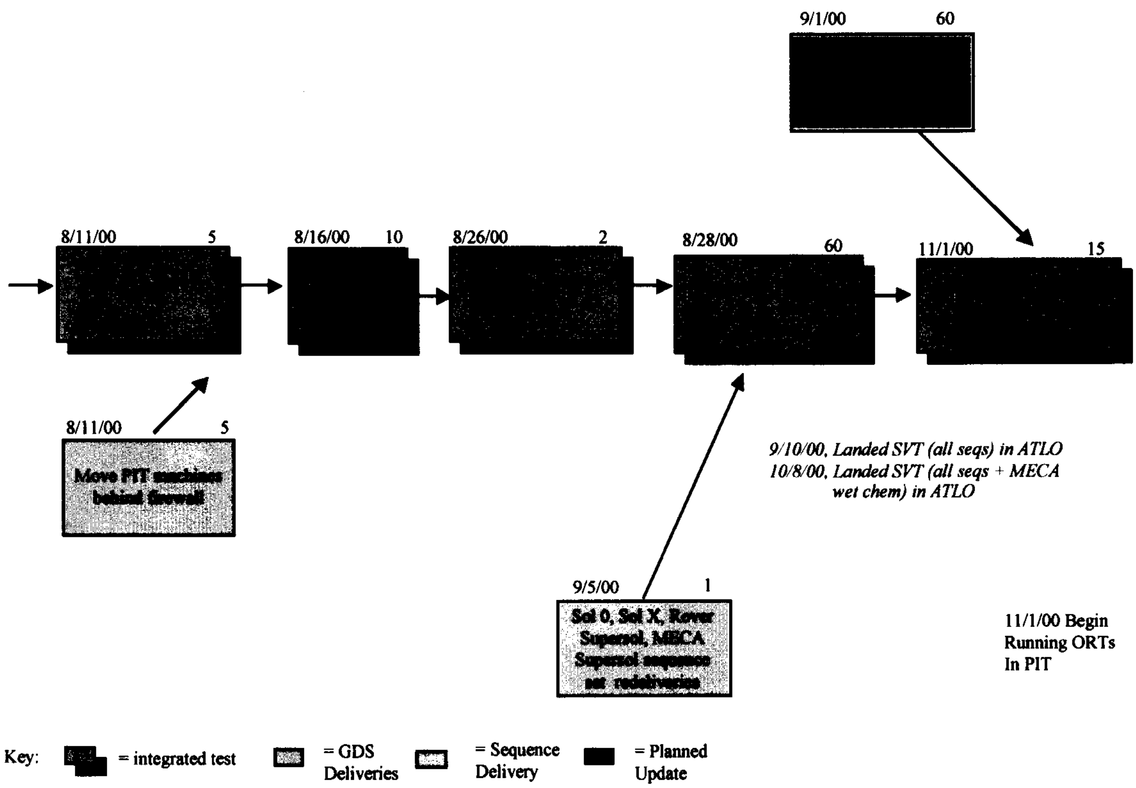

Figure 6. Integrated Test Flow (4 of 4)

configured and that no hardware or cabling was damaged during the move. Similarly, the BPIT will be executed again following integration of the LMA STL with the PIT (see Section 5).

IT #13: Sol 0, Sol X, Rover Supersol, MECA Supersol Sequence Updates— IT #13 is a collection of all sequence updates. These final sequence updates are for the SVTs to be run in ATLO in pre- and post-environmental testing.

Requirement No.	Requirement Description
Lander Payload 29.15	Move RA to grapple position
Lander Payload 29.16	Take RAC image of grapple position
Lander Payload 29.17	Take PanCam image of grapple position
Lander Payload 29.18	Grapple Rover with RA
Lander Payload 29.19	Take RAC image of Rover grapple
Lander Payload 29.20	Take PanCam image of Rover grapple
Lander Payload 29.21	Hoist Rover with RA over to just above deploy site

Requirement No.	Requirement Description
Lander Payload 29.22	Take PanCam image of Rover just above deploy site
Lander Payload 29.23	Set Rover on ground at deploy site
Lander Payload 29.25	Take PanCam Rover deploy movie
Lander Payload 29.26	Take RAC image of Rover at deploy site
Lander Payload 29.27	Take PanCam image of Rover at deploy site
Lander Payload 29.28	Disengage Rover from RA
Lander Payload 29.30	Take RAC image of disengaged Rover prior to RA retraction.
Lander Payload 29.31	Retract RA
Lander Payload 29.32	Take PanCam image of disengaged Rover

Some requirements will be satisfied during the integration of the payload hardware into the PIT. All payload requirements verified in the PIT will completed prior to verification in ATLO. The PIT will also verify those payload requirements that cannot be verified in ATLO on the flight vehicle (i.e., soil delivery and digging with the RA scoop); these are tracked in the verification matrix as well.

PIT Upgrade: The STL

To provide the highest level of fidelity in a testbed for the surface operations phase of the mission, it has been proposed that the LMA STL be delivered to JPL and integrated with the PIT. The STL is essentially the test platform for the lander vehicle and its subsystems. The avionics subsystem, including the RAD6000 processor and PACI cards, is integrated in the STL with a closed-loop simulation environment where Mars '01 cruise phase and Entry, Descent & Landing (EDL) phase tests can be performed. The PIT Lander Sim environment will be replaced by the STL to allow the full-up FSW to run on the flight processor and interface to the PIT payloads though the flight PACI boards. Currently, plans are proceeding to convert a Mars '98 STL to the Mars '01 configuration and deliver this system to JPL in June '00. Dedicated personnel will be responsible for understanding and maintaining the STL hardware, FSW and simulation environments. The STL will be moved with the PIT to the new test facility in August '00. Once the operators have gained adequate experience with the STL, the two testbed systems will be integrated together. This high-fidelity testbed will then be used for operational readiness testing in support of the Mars '01 mission after launch.

Operational Readiness & Performing the Landed Mission

The Mars Surveyor Operations Project is committed to training operations personnel to ensure the landed mission success. The design of the mission mandates operations personnel with a broad based and comprehensive understanding of the lander payloads and how they work together to ensure quick turnaround of landed sequences which is required for success on the surface of Mars. The PIT is the facility where these personnel will be trained as a function of their experience conducting the integrated tests and sequence verification tests described earlier. In November '00, the PIT will begin conducting operational readiness tests where all elements of the mission operations team will come together to validate procedures, sequences, and team interactions in flight-like scenarios in preparation for the April '01 launch of the lander.

5. CONCLUSION

Satisfaction of the Mars '01 Lander's primary mission objectives relies heavily on the interaction of the various payloads and the teams developed to respond to the mission goals. The ATLO phase of every spacecraft's development is notoriously constrained by the schedule to get to the launch pad. Likewise, excessive testing on flight articles can be risky and problems uncovered at that stage of the program may not be recoverable. The PIT is designed to reduce the risk of ATLO and landed operations. Testing payload functionality prior to flight payload integration on the lander, and performing the dry-run service of landed sequences will avoid significant cost increases and schedule delays in ATLO. Furthermore, activities supported by the PIT and the training of its personnel will enable the maximum science return from the mission once we are on the surface of Mars.

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6. BIOGRAPHY

Paula Pingree *is a Senior Staff Engineer in the Avionics Systems Section at JPL. At JPL, she has been the Command & Data Handling Subsystem Lead for Mars Global Surveyor, a member of the Cassini Integration & Test Laboratory team, the Deep Space One Testbed Lead, and most recently she led the Phase A I&T study team for the Mars Ascent Vehicle (an element of the Mars Sample Return Project). Currently she is the Mars '01 Payload Interoperability Testbed Lead. Before coming to JPL, she worked for GE Astro Space / Martin Marietta in NJ & PA. There she was part of the Mars Observer (MO) spacecraft development team and later spent two years at JPL as part of the MO Operations Team. She has a Bachelor of Engineering degree from Stevens Institute of Technology in Hoboken, NJ, and is currently pursuing an MSEE degree from California State University Northridge.*